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Award Number: DAMD17-00-1-0693

TITLE: A Novel Technique for Percutaneous Vertebroplasty in the Treatment of Metastatically Involved Vertebral Bodies

PRINCIPAL INVESTIGATOR: Cari M. Whyne

CONTRACTING ORGANIZATION: Sunnybrook and Women's College Health Sciences Centre
Toronto, Ontario M4N 3M5 Canada

REPORT DATE: September 2001

TYPE OF REPORT: Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2001	Final (1 Sep 00 - 31 Aug 01)

4. TITLE AND SUBTITLE
A Novel Technique for Percutaneous Vertebroplasty in the Treatment of Metastatically Involved Vertebral Bodies

5. FUNDING NUMBERS
DAMD17-00-1-0693

6. AUTHOR(S)
Cari M. Whyne

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Sunnybrook and Women's College Health Sciences Centre
Toronto, Ontario M4N 3M5 Canada

E-Mail: cari.whyne@swchsc.on.ca

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Report contains color

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. Abstract ***(Maximum 200 Words)*** *(abstract should contain no proprietary or confidential information)*
Metastatic disease to the spine occurs in up to one third of all cancer patients. Over 50% of spinal metastases with neurologic manifestations in females are found to arise from primary breast neoplasms. Percutaneous vertebroplasty is a minimally invasive procedure designed to provide stability to structurally weakened vertebrae due to osteoporosis or lytic lesions. In percutaneous vertebroplasty, clinically significant complications occur predominantly in patients with spinal metastases. We proposed that this higher complication rate may be due to generation of elevated intervertebral pressures and movement of tumor tissue during the prophylactic (pre-fracture) injection of cement into vertebral bodies containing highly incompressible lytic lesions. We hypothesized that removing tumor prior to or during the injection of bone cement can reduce pressures and tumor extravasation. Consequently, this may improve the filling pattern, resulting in improved spinal stability. This work aims to develop a novel method for percutaneous tumor ablation and to quantify its ability to improve vertebroplasty results in metastatically involved vertebrae. The results of this study will provide a basis for clinical investigations into the improvement of vertebroplasty techniques and outcomes for patients treated prophylactically for spinal metastases.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Surgical, Clinical and Experimental Therapeutics	18
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

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Introduction

Metastatic disease to the spine occurs in up to one third of all cancer patients (Wong et al., 1990). Over 50% of spinal metastases with neurologic manifestations in females are found to arise from primary breast neoplasms (Constans et al., 1983). With improvement in adjuvant therapies, longer life expectancies for breast cancer patients make long-term quality of life an important consideration in treatment, especially for those with vertebral body metastases. For these patients quality of life depends on how effectively we treat the symptoms arising from metastases. Vertebral metastases are a particular problem as they affect patient mobility due to the pain of pathological fracture or from pressure on neurological structures (i.e. canal compromise due to fracture fragments or tumor expansion). Radiation and chemotherapy may help to slow tumor growth but they do not restore stability to a mechanically compromised vertebral body. Percutaneous vertebroplasty is a minimally invasive procedure designed to provide stability to structurally weakened vertebrae due to osteoporosis or lytic lesions. It is a radiologically guided therapeutic procedure that consists of percutaneous injection of surgical cement into the vertebral body. This procedure can provide immediate, long-term pain relief and contribute to spinal stabilization. The cement strengthens the vertebral body and there is approximately 85% of patients experience significant pain relief regardless of the pathology or the etiology of their vertebral fracture. In percutaneous vertebroplasty, clinically significant complications occur predominantly in patients with spinal metastases (Deramond et al, 1998). The frequency of complications is 1.3% in osteoporosis, 2.5% in spine angiomas and 10% in metastatic disease (Chiras et al, 1997). We propose there may be generation of elevated intervertebral pressures during the injection of cement into prophylactically treated (pre-fracture) vertebral bodies containing highly incompressible fluid-filled lytic lesions. Higher intervertebral pressures can potentially lead to bursting of the vertebral body with retropulsion of tumor, bone or cement into the spinal canal and irreversible neurologic compromise. There is also evidence in several animal and human studies that elevated internal pressures developed in bones can cause pulmonary embolization (Hofmann et al., 1999). The generation of vertebral pressures and extravasation of tumor tissue during cement injection may be responsible for this elevated clinical complication rate. The overall aim of this research project was to quantify the biomechanical behaviour of percutaneous vertebroplasty in the metastatic spine, identify factors that may lead to the higher complication rates seen clinically, and to develop a novel method to improve the procedure for the prophylactic treatment of vertebral metastases.

Body

Objective 1: Develop a model to study vertebroplasty in the metastatically involved spine

An initial model to study vertebroplasty in the metastatic spine was developed using calf spinal tissue. Calf spines were obtained from the school of veterinary medicine at the University of Guelph. The spines were stored at –20°C, thawed at room temperature and heated to 37°C in a saline bath prior to testing.

To model metastatic involvement, a simulated defect was introduced into the vertebral body trabecular centrum. A 16 mm diameter hole was cored into the trabecular centrum through the lateral wall, 60% of the transverse diameter of the vertebra (without breaking through the opposing vertebral wall). The core was removed from the centrum and the defect was filled with simulated metastatic tumor. The core was dissected to yield an end-cap of trabecular bone and cortical shell to close the lesion inside the vertebral body (Figure 2). The core end-cap was reattached to the vertebral body using PMMA, filling all gaps for a tight seal.

Initially a 0.5% solution of agarose gel was used to simulate the tumor, formulated to mimic the average material properties of lytic metastatic specimens (Whyne et al., 2000). However, the behaviour of this gel was not able to adequately represent the motion of the tumor as it was displaced by the bone cement. This may have been due to the connectivity of the gel and its behaviour when subjected to heat (as the bone cement thermally sets). As well, in order to understand the challenges associated with tumor removal, a more realistic simulation of the metastatic tissue was needed. To better model the behaviour of the metastasis, fresh frozen primary tumor tissue samples obtained from the Department of Pathology, Sunnybrook and Women's College Health Sciences Centre, were used to fill the defect. Ideally, metastatic tumor harvested from bone would have been used to fill the lesions, however obtaining sufficient amounts of such tissue was not possible.

Cannulae were placed bilaterally into the anterior 1/3 of the vertebral body via an intrapedicular technique (Figure 1). One cannula was attached to the syringe for percutaneous injection of bone cement while the other cannula was attached to a pressure probe (CDX3, COBE Canada) to measure intervertebral pressures. Following attachment of the cannulae, fluid was injected into the trabecular centrum via the cannulae to remove any potential air pockets introduced into the trabecular centrum. Simplex P (Stryker, USA) bone cement is widely used for percutaneous vertebroplasty, and was utilized for all testing in this study.

Each experiment commenced with mixing of the cement monomer and powder according to product guidelines. The cement was then poured into a 10mL syringe. The syringe was attached to the injection cannula and supported on a frame attached to the materials testing machine (MTS Bionix 858) (Figure 3). A steel plunger, customized to fit the 10 mL syringe, was attached directly to the to the linear actuator of the MTS. Cement injection commenced within 180 to 310 seconds following monomer/polymer mixing at a rate of 1mL per 20 seconds in order to simulate clinical injection rates. Intervertebral pressures and injection forces were measured both during and subsequent to the injection. Following the experimental testing, the vertebrae were sectioned and digitally photographed to visualize the motion of the cement and tumor tissue (Figure 4).

Initial measurements were made to quantify injection forces required to pass the cement from the syringe through the 11-gage cannula. The injection system (plunger, syringe and cannula) was attached to the experimental apparatus with no vertebrae attached. Injection forces up to 900N were developed at an injection rate of 1mL per 20 seconds (Table 1) and were dependent on the time from initial mixing of the cement, cleanliness of the cannula (i.e. no cement residue), couplings not affected by the chemical compounds in the cement, and cannula length and end taper. Use of a clean cook needle without plastic coupling reduced pressures to 490N after 9 mL of cement was injected even with a long (500 second) delay from monomer/polymer mixing to the commencement of injection. Minimizing and recording the time from cement mixing to injection is an important parameter in quantifying injection forces, in addition to cannula condition and design. Clean cannulae without plastic couplings were selected for use in performing the vertebroplasties.

The experimental vertebroplasty was performed on intact calf vertebrae and adjacent vertebrae with simulated metastases. Even with the design changes to the cannula, high pressures were developed in both the calf spines with and without defects during injection (Table 2). High injection forces initially caused bursting of the 10 mL syringes, so a supporting collar was made for the syringe and attached to the testing apparatus. To further reduce the incidence of syringe failure, the cannula was shortened, removing the end taper. The high pressures developed in the calf model can be explained by the high bone density and the small size of the vertebrae. As well, the presence of a growth plate may have reduced the effective volume into which the cement was injected.

Successful development of this calf spine model and testing protocol for percutaneous vertebroplasty was then transferred to a human spine model.

Objective 2: Quantify pressurization from traditional vertebroplasty in intact and metastatically involved vertebrae. Determination of tumor motion during vertebroplasty

Spinal tissue was harvested from fresh frozen cadavers obtained through the Division of Anatomy, University of Toronto. The average age of the donors was 77 ± 11 years (range 62 to 93 years). The specimen details are listed in Table 3a. The specimens were stored at –20°C, and thawed at room temperature prior to testing. Anteroposterior and lateral radiographs of the frozen specimens were obtained to rule out any gross pathologies in the specimens. Spinal motion segments consisting of 2 or 3 vertebral bodies were utilized. On each segment, a metastatic defect was introduced into one vertebral body following the same procedure as outlined for the calf spines. To better visualize the motion of the tumor tissue within the simulated defects, the tumor tissue was soaked in green dye prior to insertion. Bipedicular cannular insertion allowed attachment of the pressure sensor and injection syringe. The specimens were then heated to 37°C and the cannulae filled with saline, prior to their attachment to the experimental apparatus and cement injection. Following testing of the specimens, the removed cores were cleaned and defatted. The core specimens were measured and weighed to determine their trabecular apparent densities.

To date, four spinal motion segments have been tested with and without metastatic involvement (2 lumbar and 2 thoracic) (Table 3b, Figures 5,6) due to the limited availability of fresh frozen tumor specimens. Maximum pressures generated in the lumbar vertebrae ranged from 0.25 kPa to 0.98 kPa (Figure 7). In the lumbar specimens, higher pressures were not seen due to the inclusion of the tumor as compared to the intact adjacent vertebrae. Higher pressures were developed in the thoracic vertebrae, from 0.52 kPa to 21.7 kPa, as compared to the lumbar specimens. One thoracic specimen demonstrated a substantial increase in pressure with tumor inclusion, while the other specimen developed higher pressures in the intact vertebral body.

Intervertebral pressurization was directly related to the amount of cement injected into the vertebral body. Clinically, the aim of vertebroplasty is to achieve cement fill of the anterior 60% of the vertebral body. The amount of cement injected in our model (4 to 8 cc) is clinically appropriate for achieving this desired fill. An additional factor that may affect vertebral body pressurization is the rate of cement injection. While utilizing a slower rate of injection may help to reduce intervertebral pressurization, time constraints due to hardening of the cement do not allow for very slow fill.

Bone density of the specimens ranged from 0.111 to 0.187 g/cm^3. With the limited number of human specimens tested, no relationship between bone density and pressurization can be elucidated from the data. However, significantly higher pressures were seen in the higher density calf spines. Further testing of additional specimens is needed to determine any relationship between bone density and pressurization during vertebroplasty in the human vertebrae.

Vertebral volumes ranged from 18937 mm^3 to 55870 mm^3 in the thoracic and lumbar segments. Vertebral level and size may be important parameters in the likelihood of tumor pressurization. Pressurization was markedly higher in the thoracic as compared to the lumbar vertebrae tested, and in more superior thoracic levels. Further testing of lumbar and thoracic vertebrae will elucidate these relationships further and may result in different clinical protocols for the application of vertebroplasty based on spinal levels and vertebral body size.

Pressures developed in the human vertebrae ranged up to 21.7 kPa. In characterizing the risk of emboli from intervertebral pressurization, pressures developed within the proximal femur exceeding 20 kPa (150mmHg) are thought to be responsible for fat emboli to the lungs in dogs (Orsini et al, 1987). Snow flurry (small amounts of bone marrow intravasation) has been characterized at intramedullary pressure levels of 6.7 kPa (50 mmHg) in sheep, with configured emboli appearing at 26.7 kPa (200 mmHg) (Wenda et al, 1993). Thus pressure levels developed in this work are sufficiently elevated in some cases to realize the risk of embolic complications. Moreover, injection of cement into lytic lesions causes displacement of tumor tissue which can result in its movement into the vascular system, potentially increasing the likelihood of embolic complications. In osteoporotic vertebrae, the presence of fractures and high porosity of the trabeculae and cortical shell may prove to reduce vertebral body pressurization during cement injection, however with the presence of a metastatic lesion this permeability may enhance the likelihood of tumor extravasation even at reduced pressures.

Limitations to this model arise in that it may be possible that the method of defect preparation can introduce voids or air pockets into the centrum. Particularly, in the lumbar vertebrae tested,

the amount of tumor tissue available to simulate the lesion was small and may have not been able to fully fill the defect and integrate into the surrounding trabeculae. This may have resulted in the lower pressures generated in these vertebrae as compared to the adjacent intact specimens. Larger volumes of available tumor should enable a more complete filling of the core (as was possible in the thoracic specimens due to the receipt of additional tumor tissue prior to their testing). Lower values of pressurization may also occur as the tumor may not be sufficiently integrated into the simulated lesion as compared to a tumor which has grown inside the bone. This may make the tumor more deformable resulting in the development of less pressurization. Scheduled testing of additional specimens with sufficient tumor tissue available will enable resolution of this issue, and allow a statistical analysis of our results.

While the green dye enabled visualization of the tumor tissue in the vertebral sections post vertebroplasty, further improvements are planned to better visualize the tumor tissue motion during injection and allow quantification of this motion. Tumor tissue will be presoaked in contrast enhancing fluid prior to insertion in the defect to allow visualization of the tumor tissue under fluoroscopy. PMMA will be used for the injection rather than Simplex P to better distinguish the tumor vs. cement tissue under fluoroscopy (Simplex P contains barium sulphate to enhance its radio-opacity). Real-time digital video fluoroscopic video will be captured during the injection. Following the injection the video will be digitally analyzed to quantify the motion of the tumor tissue, using commercial image processing software (Anaylze 3.1).

Objective 3: Develop a novel method for percutaneous removal of tumor within vertebrae to be used in conjunction with vertebroplasty

Removal of the tumor tissue is hypothesized to result in reduced pressurization, reduced likelihood of tumor extravasation and improved vertebral fill, through the creation of a space for the cement within the vertebral body. Three methods were investigated for percutaneous removal/ablation of tumor tissue: vacuum suction, radiofrequency ablation and interstitial laser ablation. In researching and selecting a tumor ablation method, we imposed design constraints that would not significantly alter the existing clinical procedure. The method must: 1. Access the tumor using the existing cannula (<2.83 mm diameter), 2. Provide effective tumor ablation in a reasonable period of time (<15 min), and 3. Not add prohibitively to the cost of the vertebroplasty.

Vacuum Suction

Initially a vacuum suction technique was proposed for removal of the tumor tissue within the vertebral body. However, due to the small diameter of the cannula used in the vertebroplasty procedure (11 gage needle), blocking of the suction is a limitation of this technique unless the tumor tissue can be easily disintegrated into smaller pieces. Clinically, since it is not desirable to move the cannula around within the vertebral body following accurate placement, dislodging of tip blockage would present difficulties. Incorporation of vacuum suction with a technique for tumor disintegration, although a potential solution, may be more complex than a single method for ablation.

RF Coblation

The Nucleoplasty RF Coblation system was designed for ablation of the nucleus pulposus within the intervertebral disc. Using this system, ablation of tissue is achieved by molecular disassociation rather than through heating. RF coblation gives a controlled thermal effect with minimal collateral tissue necrosis. The coblator can be introduced into the vertebral body under fluoroscopic guidance through the injection cannula (fits into a 17 gage needle). The coblator is able to ablate tumor tissue in a similar fashion to the nucleus pulposus of the disc (Figure 8), however, there are some important limitations to the use of this technique. A small probe must be used due to space restrictions in the cannula, and since ablation time is inversely related to the probe size, this does not provide a rapid method for tissue ablation. As well, only the area directly adjacent to the wand is removed, creating a 1 mm channel of ablation. While the tip of the wand is slightly angulated to allow some movement of the wand, the reach of the canal for ablation is restricted by the placement of the cannula. Charring/destruction of the wand was noted when attempting to ablate larger volumes of tumor tissue ex vivo with the small wand. As the tissue chars, insufficient fluid for additional ablation can lead to probe damage. Thus a fluid/suction attachment might be necessary, that could limit the use of this device within the existing cannula. Finally, aside from the cost of the RF unit, the probes are designed for single use applications at a high cost per use (900 CAD per probe). Current equipment costs for vertebroplasty are in the range of 200 CAD. Therefore, the clinical feasibility of utilizing this type of apparatus may be limited.

Interstitial Laser Coagulation

A variety of lasers were considered for this application of intervertebral tumor ablation including Holmium, CO2 and YAG lasers. Diode lasers have been shown to be able to produce predictable tumor ablation in relation to the energy supplied (Harries et al., 1994) This type of laser also has a chromophore of haemoglobin, making it particularly suitable for the ablation of the highly vascular tumor tissue while reducing its potential effects on the surrounding (white) bone. The price for this type of portable semi-conductor laser is considerably less than other laser options (The initial start up cost for this device is 44,000 CAD for the generator and 5 multi-use fibres cost 1,600 CAD). Using this system, a wavelength of 805 nm can be administered through a 400 μm fibre that easily fits in the vertebroplasty cannula (11 gage needle). Interstitial laser coagulation with a precharred fibre has been shown to produce predictable diameters of necrosis within mammary tumors with few complications (Harries et al., 1994). Previous work has shown that a necrosis diameter of 14mm can be achieved in 500 seconds @ 2 Watts (1000 Joules) (Harries et al., 1994). A protocol for quantification of the associated volumetric reduction of tumor has been developed and testing of this is presently underway utilizing a laser borrowed from the department of Medical Biophysics, Princess Margaret Hospital, University of Toronto. Additional surgery time using this technique should be well within the 15-minute limit including fibre placement (under fluoroscopy) and ablation.

From our preliminary investigations, a laser approach to tumor ablation may be best suited for use in conjunction with percutaneous vertebroplasty. Delays in completing the quantification of the volumetric reduction of tumor using this method have been hampered by the availability of fresh frozen tumor specimens.

Objective 4: Quantification of spinal stability and burst fracture risk pre and post vertebroplasty with and without tumor ablation

Eight thoracolumbar spinal motion segments consisting of 6 vertebrae have been harvested from fresh frozen cadavers obtained through the Division of Anatomy, University of Toronto. Anteroposterior and lateral radiographs of the frozen specimens have ruled out any gross pathologies in the specimens. Each 6 vertebrae spinal motion segment was then further divided into a 3-vertebra motion segment (T12-L1-L2 and L3-L4-L5), with the middle vertebrae (L1 and L4) receiving vertebroplasty. On each segment, a metastatic defect will be introduced into the middle vertebral body following the same procedure as outlined earlier. Spinal canal displacement as a measure of burst fracture risk will be measured during all testing (Whyne, 1999). To do this, a canal displacement sensor consisting of 2 uniaxial strain gages attached to a thin curved brass beam is inserted into the spinal canal and secured to an attachment device on the posterior vertebral body wall using a small rare-earth magnet. The other end of the device is clamped to an attachment on the anterior-superior spinous process. The inferior and superior vertebrae are then potted in PMMA and attached to the MTS machine. The fixture on the MTS is aligned to allow only axial compressive loading to the specimens. A 100 N compressive preload will be applied to each motion segment. The specimens are then loaded in axial compression to a level of 800N at a rate of 3200 N/s. Outcome variables of axial displacement and load induced canal narrowing will be recorded.

Following testing, the metastatically involved specimens will be prepared for vertebroplasty. The cannulae will be inserted bipedicularly into the specimens and heated to 37°C in a saline bath. The metastatic lesion in one of each of the motion segment pairs will be ablated using the interstitial laser technology while the tumor of the paired specimen will be left undisturbed prior to injection. To ablate the tumor, laser energy will be applied via an optical fiber placed through the cannula delivering 2W of light at a 810-nanometer wavelength through a single fiber for 500 seconds (1000J). The specimens will then be injected with Simplex P cement as per the protocol described earlier. Intervertebral pressure will be recorded during injection. The injection will be done under fluoroscopic guidance to ensure fill of only the anterior 60% of the vertebral body. CT scans will be taken post-vertebroplasty to quantify the pattern and amount of fill achieved as well as geometric parameters for each vertebra.

Post-vertebroplasty, each specimen will be re-tested under axial compressive loading following the protocol described above, and subsequently tested to failure to determine the ultimate strength of the cement-augmented spinal motion segment. Bone mineral density for all specimens will again be measured by a direct technique to quantify weight and volume of the trabecular bone removed when simulating the metastases.

Results from the final stage of this study will allow statistical analysis of vertebral pressurization, canal narrowing as a measure of burst fracture risk and ultimate spinal motion segment strength. These parameters will allow the determination of the potential biomechanical benefits of tumor ablation prior to vertebroplasty in the metastatically involved spine.

Key Research Accomplishments

- Developed an experimental in vitro model for studying percutaneous vertebroplasty in the metastatically involved spine.
- Quantified vertebral body pressurization due to cement injection and injection forces required for cement insertion in intact and metastatically involved vertebrae.
- Examined relationships between bone density, vertebral level, size and vertebral body pressurization from cement injection.
- Developed a technique for studying the path of tumor/cement during percutaneous vertebroplasty.
- Developed a novel method for percutaneous volumetric ablation of tumor tissue within vertebrae using laser technology.

Anticipated research accomplishments

- Quantify the ability of the interstitial laser to volumetrically reduce tumor volume within the vertebral body.
- Compute and evaluate changes resulting from tumor ablation to pressurization, tumor movement and cement fill.
- Determine the route of cement fill and tumor dispersion during injection.
- Determine the overall effect of tumor ablation on the post vertebroplasty mechanical strength of metastatically involved vertebrae.

Reportable Outcomes

Presentations (Scheduled):

Bone Metastases Clinic Business Meeting, December 14, 2001, Toronto Sunnybrook Regional Cancer Centre

City Wide Rounds, University of Toronto, Division of Orthopaedic Surgery, February 8, 2002, Mount Sinai Hospital

Course on Management of Bone Metastases, February 22, 2002, Toronto Sunnybrook Regional Cancer Centre

Abstracts and Manuscripts in Preparation:

Vertebral pressurization and injection forces during prophylactic percutaneous vertebroplasty. *Canadian Orthopaedic Research Society*, October 15, 2001 Submission Deadline

Percutaneous vertebroplasty in the metastatic spine: The effects of vertebral level, size and bone density on pressurization, tumor extravasation and cement fill. *Spine*

Academic Training / Research Opportunities Supported by this Award:

Declan Reidy, Orthopaedic Spine Fellow, Sunnybrook and Women's College Health Sciences Centre, University of Toronto

Payam Mousavi, BSc Candidate, Engineering Science, University of Toronto

Henry Ahn, Orthopaedic Surgery Resident, Division of Orthopaedics, University of Toronto

Conclusions

This grant has opened up a novel area of research for our laboratory in the area of percutaneous vertebroplasty treatment for spinal metastases. Delays in completing the vertebral testing and the quantification of the volumetric reduction of tumor have been hampered by the availability of fresh frozen tumor specimens. We have recently improved coordination for obtaining these specimens, allowing work on the project to progress.

For future expansion of this work, we have submitted a proposal for funding to the PREA (Premier's Research Excellence Awards) program entitled "Biomechanical modeling of percutaneous vertebroplasty in the metastatically involved spine" which aims to extend the experimental techniques developed and combine them with computational research methods and application to clinical patient data. Integrating computational modeling and experimental testing will greatly enhance the potential of this research to identify specific factors and resolve complications associated with percutaneous vertebroplasty in the metastatic spine. This comparative analysis will allow the biomechanical determination of optimal methodologies and threshold levels, particularly for treating multi level tumor involvement. This includes investigation of research questions aimed at examining preferential locations and devices for cement injection as well as the optimization of cement volumes and injection protocols, to further reduce the possibility of pressurization and tumor extravasation without compromising post-vertebroplasty strength.

Percutaneous vertebroplasty has been shown to provide high rates of success in spinal stabilization and pain relief. However, concern as to the higher complication rate when treating patients with metastatic lesions may lead to fewer such patients being offered this beneficial treatment. By providing insight into pressures generated by the cement and its filling pattern, this work may explain why patients with vertebral metastases are more likely to have complications associated with percutaneous vertebroplasty. The addition of a tumor ablation step to the procedure may ultimately help reduce this elevated complication rate and make percutaneous vertebroplasty safer and more effective for patients with metastatic disease. Ultimately, the novel research embarked upon during this study will lead to improved instrument design, new clinical techniques, and optimized clinical protocols for percutaneous vertebroplasty. Finally, future clinical testing will yield the impact of these developments which may significantly reduce complications and improve quality of life for patients with metastatic breast cancer.

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Appendix A: Tables

Trial	Cannula	Time after Mix (seconds)	Amount of Cement Injection 1ml	2ml	3ml	4ml	5ml	6ml	7ml	8ml	9ml	
A	Reused/Coupler	270	49	288	646	811	896	Syringe failed (at 910N)				
B	Reused/Coupler	185	31	73	223	458	602	Syringe disengaged				
C	New/No Coupler	300	55	145	185	233	282	328	386	440	491	Syringe emptied

Table 1: Cement injection forces developed through syringe/cannula.

Specimen	Amt Injected (cc)	VB Pressure (kPa)	VB Pressure @ 1/2 time (kPa)	Time at Pmax (s)	Inject Force (N)	Time to Injection (s)
C1	2.5	28	13	48	528	-
C2	4.5	95	45	64	514	187
C3	4	39	1	99	562	210
C4	4	14	4	105	520	195
C5	6	19	2	122	959	215

Table 2: Experimental results for percutaneous cement injection in calf vertebral specimens.

Specimen/ Test	Age	Sex	BD	Level	Tumor	Size (mm3)
1a	81	F	0.129	L2	Y	52870
1b	81	F	0.129	L1	N	47160
1c	81	F	0.129	L3	N	54045
2a	62	M	0.111	L2	Y	55760
2b	62	M	0.111	L1	N	41192
2c	62	M	0.111	L3	N	55870
3a	72	M	0.187	T10	Y	19494
3b	72	M	0.187	T11	N	18937
4a	93	M	0.129	T10	Y	21890
4b	93	M	0.129	T9	N	19244

Specimen/ Test	Cement Vol Injected (cc)	VB Pressure (kPa)	VB Pressure at ½ time (kPa)	Time at Pmax (s)	Injection Force (N)	Time to Injection (s)
1a	7.5	0.25	0.15	147	687.4	218
1b	7	0.65	0.45	140	539.3	190
1c	7.5	0.98	0.15	160	562.8	202
2a	4	0.17	0.1	100	564.7	232
2b	6.5	0.4	0.35	160	812.3	310
2c	7	0.3	0.3	130	518.7	215
3a	8	4.7	1.5	165	199	180
3b	7	0.52	0.4	160	744.5	260
4a	7	11.3	8.7	183	583.2	238
4b	7	21.7	7.8	171	481.7	210

Table 3: (a) Specimen parameters and (b) Experimental results for human vertebral specimens with and without simulated metastases.

Appendix B: Figures

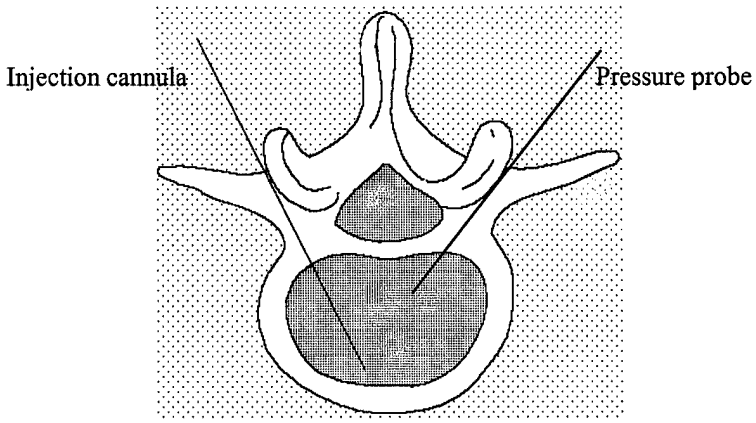

Figure 1: Schematic diagram of transpedicular cannula placement for percutaneous vertebroplasty.

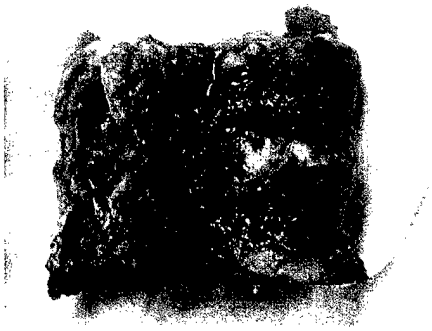

Figure 2: Simulation of metastatic vertebral body lesion.

Figure 3: Experimental set up for percutaneous vertebroplasty injection.

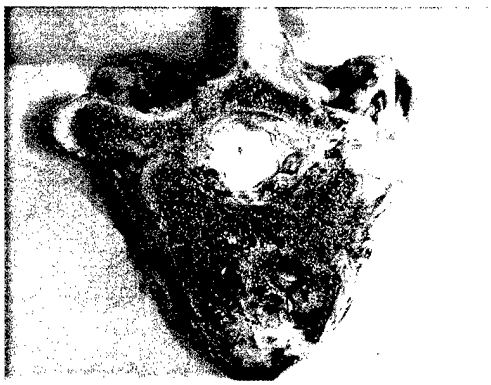

Figure 4: Transverse section of a calf spine specimen with simulated metastatic defect following percutaneous cement injection.

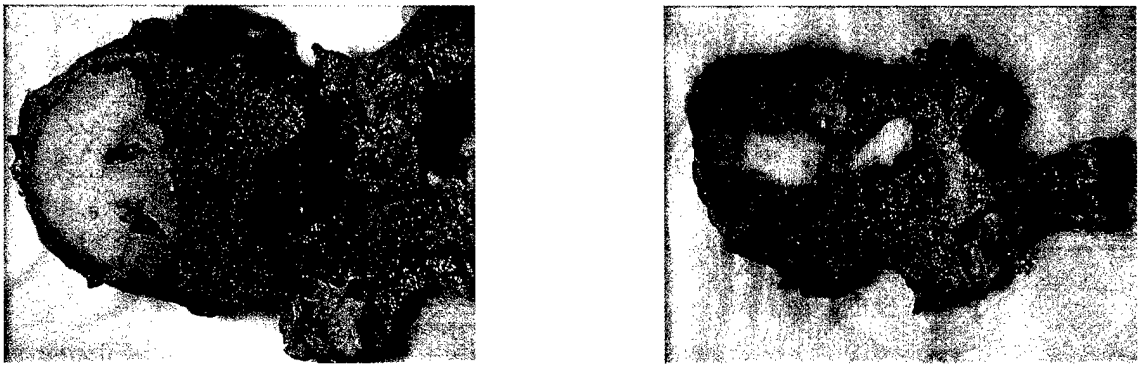

Figure 5: Transverse section of adjacent human vertebrae following percutaneous cement injection: (a) intact and (b) with a simulated metastatic defect. Note the tumor tissue has been dyed green for visualization.

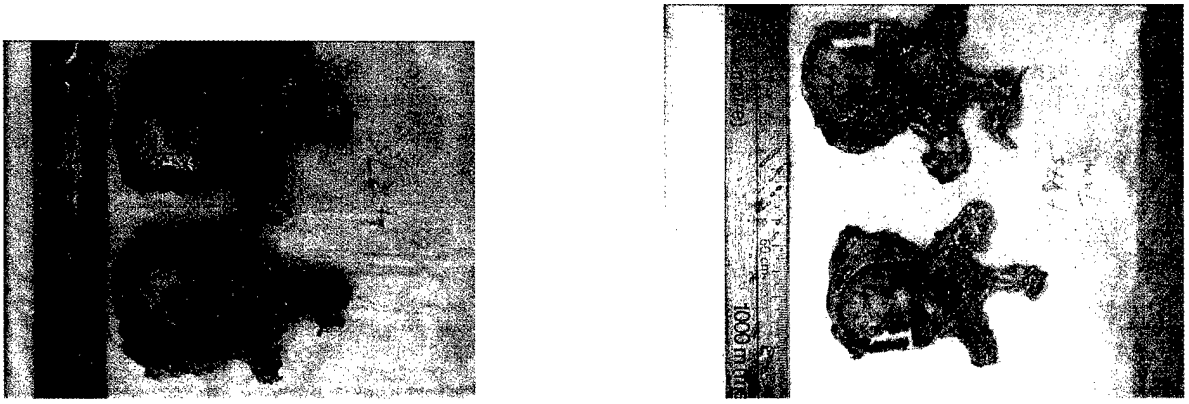

Figure 6: 2-sided transverse sections of adjacent human vertebrae following percutaneous cement injection: (a) intact and (b) with a simulated metastatic defect.

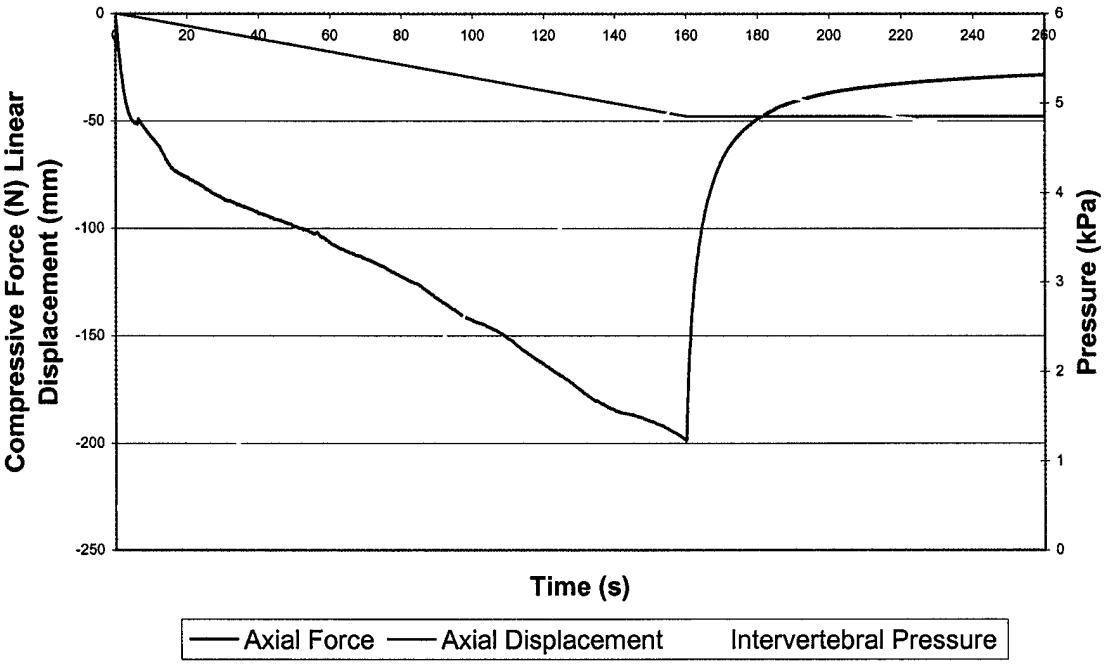

Figure 7: Pressure and injection forces developed during percutaneous vertebroplasty on a human vertebral specimen with a simulated metastasis.

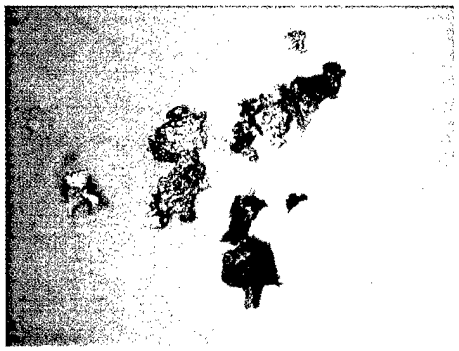

Figure 8: Tumor tissue fragments treated with RF ablation.